(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
10 October 2002 (10.10.2002)

PCT

(10) International Publication Number
WO 02/079829 A1

(51) International Patent Classification[7]: G02B 6/22, H01S 3/06

(21) International Application Number: PCT/US02/09513

(22) International Filing Date: 27 March 2002 (27.03.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/280,033 30 March 2001 (30.03.2001) US

(71) Applicant (*for all designated States except US*): **LASER-SHARP CORPORATION** [US/US]; 86 South Street, Hopkington, MA (US).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): **PO, Hong** [US/US]; 8 Town Lyne Road, Sherborn, MA 01770 (US).

(74) Agent: **DALEY, Sean, P.**; Fish & Richardson P.C., 225 Franklin Street, Boston, MA 02110 (US).

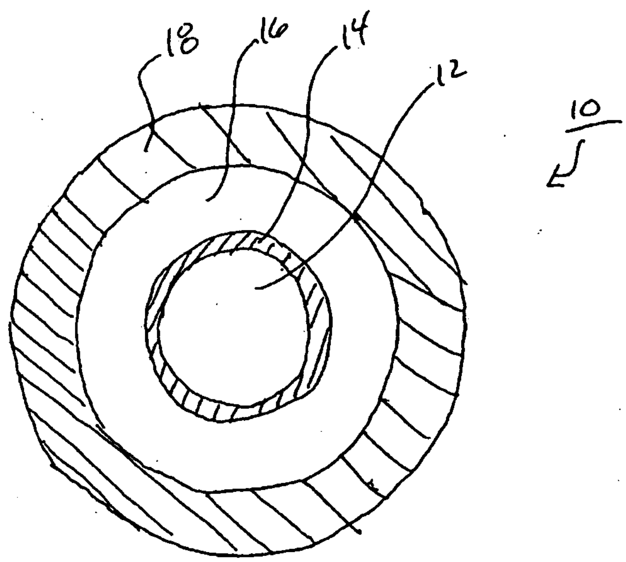
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

[Continued on next page]

(54) Title: RING CORE FIBER



(57) **Abstract:** The invention relates to fibers, such as fiber lasers, fiber amplifiers, and systems containing such fibers. In one aspect, the invention features a fiber that includes a first region (12), a core (14) and a cladding (16). The core (14) surrounds the first region (12), and the cladding (16) surrounds the core (14). Typically, the core (14) includes an active material. In a further aspect, the invention features a system that includes two fibers (10, 48). One of the fibers has a first region, a first core (e.g., a multimode core) surrounding the first region, and a cladding surrounding the core. The other fiber has a core (e.g., a single mode core). The fibers are connected so that energy can propagate between the cores of the two fibers. Typically, the core includes an active material.

WO 02/079829 A1

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

RING CORE FIBER

TECHNICAL FIELD

The invention relates to fibers, such as fiber lasers and fiber amplifiers, and systems containing such fibers.

BACKGROUND

Fibers, such as fiber lasers and fiber amplifiers, can be used to enhance absorption of pump energy. One type of fiber, commonly referred to as a double clad fiber, includes a core containing an active material, a first cladding around the core, and a second cladding around the first cladding.

SUMMARY

The invention relates to fibers, such as fiber lasers and fiber amplifiers, and systems containing such fibers.

In one aspect, the invention features a fiber (e.g., a multimode fiber) that includes a first region, a core and a cladding. The core surrounds the first region, and the cladding surrounds the core. Typically, the core includes an active material

In a further aspect, the invention features a system that includes two fibers. One of the fibers has a first region, a first core (e.g., a multimode core) surrounding the first region, and a cladding surrounding the core. The other fiber has a core (e.g., a single mode core). The fibers are connected so that energy can propagate between the cores of the two fibers. Typically, the core includes an active material.

Embodiments of the invention can include one or more of the following features.

The core can be ring-shaped.

The core can be a multimode core.

The core can include a rare earth-doped material.

The core can include a silica material and ions of a rare earth metal.

The first region can include a silica material.

The first region can have a lower index of refraction than the core.

The first cladding can include a silica material.

The first cladding can have a lower index of refraction of than the core.

The fiber can further include a second cladding surrounding the first cladding.

The second cladding can be formed of a polymer material.

The index of refraction of the first cladding can be greater than the index of refraction of the second cladding.

The fiber can be a multimode fiber.

The system can include one or more additional fibers. Each of the additional fiber(s) can individually be a single mode fiber or a multimode fiber. The core of each of the additional fiber(s) can individually be connected to the first core so that energy can propagate between the core and the particular additional fiber.

The system can further include an energy source.

The system can further include a coupler configured to couple energy emitted by the energy source to the core.

In certain embodiments, the fiber provides the advantage of being a multimode fiber. This can be advantageous, for example, when it is desirable to propagate a relatively high amount of energy through a relatively small amount of space. In some embodiments, the fiber is designed to be scalable. For example, the fiber can be designed so that, as its length is increased, the amount of energy (power) that can be propagated by the fiber increases (e.g., increases approximately linearly).

In some embodiments, the fiber can be designed to have a core capable of absorbing a relatively large amount of energy per unit length of fiber. In some embodiments, relative to other fibers having the same total cross-section, the fiber of the invention can have increased pump energy absorption.

In certain embodiments, the fiber can be designed to have a relatively large effective cross-sectional area. In some embodiments, this can reduce undesirable nonlinear effects.

In some embodiments, the fiber can be designed to be used in a side pump configuration and/or an end pump configuration.

In certain embodiments, a fiber can be relatively easily manufactured.

In some embodiments, a fiber can exhibit enhanced absorption. In certain embodiments, this can result from a fiber having a relatively large effective area.

In some embodiments, a fiber can exhibit relatively high stability. In certain embodiments, this can result from a fiber having a relatively short cavity length.

In some embodiments, a fiber can exhibit relatively few non-linear effects. In certain embodiments, this can result from a fiber having a relatively low power density.

In some embodiments, systems can be relatively easily developed by adding more sections. In certain embodiments, this can result from the relatively easy power scaling properties of a fiber.

Features, objects and advantages of the invention are in the summary, description, drawings and claims.

DESCRIPTION OF DRAWINGS

Fig. 1 is a cross-sectional view of an embodiment of a fiber;

Fig. 2A is a cross-sectional view of the fiber of Fig. 1;

Fig. 2B is an index profile of the fiber of Figs. 1 and 2A;

Fig. 3 is a perspective view of an embodiment of a fiber;

Fig. 4 is a graph of the self-image length as a function of inverse wavelength for an embodiment of a fiber;

Fig. 5 is a cross-sectional view of an embodiment of a system including a fiber;

Fig. 6 is a cross-sectional view of an embodiment of a system including a fiber;

Fig. 7 is a cross-sectional view of an embodiment of a system including a fiber; and

Fig. 8 is a graph of the self image length and double self image length as a function of radius for an embodiment of a fiber.

DETAILED DESCRIPTION

Figs. 1 and 2A show cross-sectional views of an embodiment of a fiber 10 having a first region 12, a ring-shaped core 14, a first cladding 16 and a second cladding 18.

Typically, core 14 includes a first material (e.g., a silica material, such as a fused silica) and at least one dopant (e.g., at least one rare earth ion, such as erbium ions, ytterbium ions, neodymium ions, holmium ions, dysprosium ions and/or thulium ions; and/or transition metal ion(s)). More generally, however, core 14 can be formed of any material (e.g., active material) or combination of materials (e.g., active materials) capable of interacting with a pump signal to enhance pump signal absorption (e.g., produce gain). In certain embodiments, core 14 is formed of fused silica doped with erbium ions.

Core 14 can optionally include certain other materials. For example, core 14 can include one or more materials to increase the index of refraction. Such materials include, for example, germanium oxide. Core 14 can include one or more materials to

decrease the index of refraction. Such materials include, for example, boron oxide. Core 14 can include one or more materials (e.g., aluminum oxide) that enhance the solubility of the rare earth ion(s) within core 14 (e.g., within silica, such as fused silica). Core 14 can include one or more materials that enhance the homogeneity of the index of refraction within core 14. An example of such a material is phosphorus pentoxide.

Generally, core 14 is designed to support multimode energy propagation. The thickness R of core 14 can vary depending upon the intended use of fiber 10. In certain embodiments, the thickness R of core 14 is less than about 15 microns (e.g., less than about 10 microns, less than about nine microns, less than about eight microns, less than about seven 10microns, less than about six microns, less than about five microns). In some embodiments, the thickness R of core 14 is at least about one micron (e.g., at least about two microns, at least about three microns, at least about four microns). In certain embodiments, the thickness of R of core 14 is from about four microns to about five microns.

Region 12 is usually formed of a material having a lower refractive index than core 14. In some embodiments, core 14 has a refractive index (n_{14}) and region 12 has a refractive index (n_{12}) so that $((n_{14})^2 + (n_{12})^2))^{1/2}$ is less than about 0.2 (e.g., less than about 0.17) and greater than about 0.05 (e.g., greater than about 0.12), such as from about 0.12 to about 0.17. Examples of materials from which region 12 can be formed include silica materials, such as fused silica materials. In certain embodiments, the refractive index of region 12 is about the same (e.g., the same) as the refractive index of core 14.

Cladding 16 is usually formed of a material having a lower refractive index than core 14. In some embodiments, core 14 has a refractive index (n_{14}) and cladding 16 has a refractive index (n_{16}) so that $((n_{14})^2 + (n_{16})^2))^{1/2}$ is less than about 0.2 (e.g., less than about 0.17) and greater than about 0.05 (e.g., greater than about 0.12), such as from about 0.12 to about 0.17. Examples of materials from which cladding 16 can be formed include silica materials, such as fused silica materials. In some embodiments, region 12 and cladding 16 are formed of the same material(s). In certain embodiments, region 12 and cladding 16 are formed of different material(s).

Cladding 18 is usually formed of a material having a lower refractive index than cladding 16. In some embodiments, claddings 18 and 16 have refractive indices (n_{18}) and (n_{16}), respectively, so that $((n_{18})^2 + (n_{16})^2))^{1/2}$ is less than about 0.6 (e.g., less than

about 0.5) and greater than about 0.3 (e.g., greater than about 0.4), such as from about 0.42 to about 0.47. Examples of materials from which cladding 18 can be formed include polymeric materials, such as, for example, acrylate resins, silicone polymers, polyurethane. Such materials can be, for example, fluorinated or nonfluorinated.

Fig. 2B is a refractive index profile of fiber 10 in an embodiment in which: the refractive index of core 14 is greater than the refractive indices of region 12, cladding 16 and cladding 18; the refractive index of region 12 is about the same as the refractive index of cladding 16; and the refractive index of cladding 18 is less than the refractive index of region 12 and the refractive index of cladding 16.

Fig. 3 illustrates the manner in which energy can propagate along fiber 10 (cladding 18 not shown). Energy focused at a point 30 on core 14 is focused at it mirror image point 32 on core 14 after propagating along core 14 for a distance L. After the energy propagates along core 14 another distance L, the energy is focused at a point 34 of core 14, which is the self image of point 30 on core 14. It is therefore possible to use fiber 10 for relatively high power transmission via fiber 10. This can be advantageous, for example, when it is desirable to use a relatively short length of fiber to transmit a relatively high power (e.g., when decreasing the length of fiber results in more stable and/or higher quality signal transmission).

Without wishing to be bound by theory, it is believed that this behavior can be explained through multimode interference phenomena as follows. An arbitrary energy distribution $A(r, \theta)$ in the object plane of an endface 35 of fiber 10 can be represented as a superposition of all waveguide modes:

$$A(r, \theta) = \Sigma a_m F_m(r, \theta)$$

where a_m are the complex amplitude coefficients (time factor $e^{-i\omega t}$ omitted). After propagating through a distance z, the energy distribution becomes:

$$B(r, \theta) = e^{i\beta 0z} \Sigma a_m F_m(r, \theta)\, e^{i\varphi m}$$

where $\varphi_m = (\beta_m - \beta_0)z$ is the phase difference between the m^{th} and fundamental mode (m=0). A good approximation yields:

$$\varphi_m \cong \pi m^2 z L_1 = -\pi m^2 h$$

where $L_1 = (N2\pi R)/\lambda$ is the effective index of the equivalent planar waveguide to fiber 10.

At a distance $z = L(h=1)$, then $B(r, \theta) = A(r, \theta + \pi)$, which is the mirror image signal. The simplest multiple image is at $h = ½$, where $B(r, \theta) = ((1-i)/2)A(r, \theta) + ((1+i)/2)A(r, \theta + \pi)$, which corresponds to the self image signal. Higher order signals can be formed in an analogous way.

Fig. 4 is a graph of calculated values using the above equations for the self-image length as a function of the inverse of wavelength of the energy (e.g., light) for a double clad fiber as shown in Figs 1 and 2A with a core radius of 33.5μ and a core radius of 66μ (calculations assume no change in refractive index caused by the pump energy). The data for a core radius of 33.5μ is scaled by a factor of 3.88, which is the square of the ratio of the radii (i.e. $(66/33.5)^2$). Fig. 4 shows that, for a given ring core radius, the self image length is substantially directly proportional to the inverse of the wavelength of the energy (the data for 33.5μ ring core radius had an R value of 0.9999, and the data for the 66μ ring core radius had an R value of 0.99998). Fig. 4 also shows that, for a given wavelength of energy, the self image length scales as the square of the ring core radius.

With this information, the ring core radius, wavelength of energy and/or self image length for a double clad fiber as shown in Figs. 1 and 2A can be manipulated in a relatively predictable fashion. Generally, if the self-image length for such a fiber is known at a given wavelength of energy and ring core radius, one of these parameters can be varied in a predictable fashion when the other two variables are kept constant. As an example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate self image length can be determined *a priori* when the ring core radius is varied and the wavelength of energy is kept constant. As another example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate wavelength of energy can be determined *a priori* when the self image length is varied and the ring core radius is kept constant. As a further example, if the self image length for such a fiber is known at a given wavelength of energy and ring core radius, the appropriate ring core radius can be determined a priori when the wavelength of energy is varied and the self image length is kept constant. Other examples will be apparent to those skilled in the art.

Fig. 5 shows a fiber laser system 40 in which fiber 10 is used as a gain medium. An energy source 42 emits a pump signal 44 is coupled to fiber via a coupler 46 (e.g., a V-shaped groove, such as a 90° V-shaped groove, cut into claddings 16 and 18 on the

side of fiber 10; a removed portion of cladding 18 that is replaced with a prism having substantially the same refractive index as cladding 16; a removed portion of cladding 18 that is replaced with a coupling window; or the like).

A single mode fiber 48 having a core 47, a cladding 45 and a reflective element 87 (e.g., a grating) is connected to core 14 at one end of fiber 10 so that core 47 is connected to core 14. A single mode fiber 50 having a core 49,a cladding 51 and a reflective element 85 (e.g., a grating) is connected to core 14 at a different end of fiber 10 so that core 49 is connected to fiber 14. Fiber 48 can be a passive single mode fiber or an active single mode fiber, and fiber 50 can be a passive single mode fiber or an active single mode fiber. Typically, in embodiments in which fibers 48 and 50 are passive single mode fibers, cores 47 and 49 are formed of silica (e.g., fused silica) and one or more materials (e.g., germanium), and claddings 45 and 51 are formed of silica (e.g., fused silica). Examples of single mode fibers are known to those skilled in the art and are contemplated. Generally, in embodiments in which fibers 48 and 50 are active single mode fibers, cores 47 and 49 are formed of silica (e.g., fused silica) and an active material, and claddings 45 and 51 are formed of silica (e.g., fused silica). Examples of active single mode fibers are disclosed, for example, in "Rare Earth Doped Fiber Lasers and Amplifiers," edited by Michael J.F. Digonnet (1993), which is hereby incorporated by reference.

Typically, the dimensions of fibers 48 and 50 are selected so that there is good mode matching between core 14 and cores 47 and 49. In some embodiments, this can be achieved by selected cores 14, 47 and 49 to have substantially the same diameter size.

Fiber 10 has a length L so that the respective positions at which the single mode cores of fibers 48 and 50 are connected to core 14 are diametrically opposed (mirror image). Fibers 48 and 50 have elements 87 and 85, respectively. Elements 87 and 85 are designed to reflect energy at a desired wavelength (λ_{out}). Cores 14, 47 and 49 contain one or more materials (e.g., active material(s)) that interact(s) with the pump signal so that elements 87 and 85 provide a lasing cavity for energy at λ_{out}, and fiber 10 acts as a gain medium for energy at λ_{out}. In certain embodiments, the reflectance (e.g., less than 100%) of element 87 for energy at λ_{out} is substantially less than the reflectance (e.g., about 100%) of element 85 for energy at λ_{out} so that a portion of the energy at λ_{out} passes through element 85. While shown in Fig. 5 as having a length L, fiber 10 in

system 40 can more generally have any odd integer length of L (e.g., 3L, 5L, 7L, 9L, 11L, etc.) while maintaining the relative positions of fibers 48 and 50 unchanged (e.g., diametrically opposed).

Fig. 6 shows a fiber laser system 60 in which fiber 10 is used as a gain medium has a length 2L. In this embodiment, the respective positions at which the single mode cores of fibers 48 and 50 are connected to core 14 are a self image. While shown in Fig. 6 as having a length 2L, fiber 10 in system 60 can more generally have any even integer length of 2L (e.g., 4L, 6L, 8L, 1 OL, etc.) while maintaining the relative positions of fibers 48 and 52 unchanged (e.g., self image configuration).

Fig. 7 shows a fiber system 70 in which fiber 10 is used as a gain medium. The core of single mode fiber 48 is connected to core 14 at one end of fiber 10, and the other end of fiber 10 is coated with a reflective material 72 (e.g., a mirror, such as a broad band mirror) so that element 87 and mirror 72 provide a lasing cavity for-energy λ_{out} and fiber 10 acts as a gain medium for energy at bout. In these embodiments, mirror 72 can reflect substantially all (e.g., about 100%) of energy at λ_{out}, and element 87 can reflect less (e.g., less than about 20 100%) of energy at λ_{out} so that a portion of the energy at λ_{out} passes through element 87. In these embodiments, fiber 10 can have a length that is an integer number of L (e.g., L, 2L, 3L, 4L, 5L, 6L, etc.), or fiber 10 can have a length that is not an integer number of L.

While Figs. 5-7 show certain embodiments of fiber 10 in a fiber laser system, other arrangements will be apparent to those skilled in the art. For example, fiber 10 can be used 25in fiber amplifier systems and/or systems that contain both fiber lasers and fiber amplifiers. Examples of fiber laser systems and fiber amplifier systems in which fiber 10 can be used are disclosed, for example, in commonly owned U.S. Provisional Patent Application Serial No.__________ filed on February 7, 2001, and entitled, "Raman Fiber Laser," and in commonly owned U.S. Patent Application Serial No.____________, filed on March 2, 2001, and entitled, "Fiber For Enhancing Energy Absorption," both of which are incorporated by reference herein.

While certain embodiments of the invention have been disclosed herein, the invention is not limited to these embodiments. For example, in certain embodiments, the fiber 10 can have any design appropriate to support multimode energy propagation. For example, fiber 10 can include multiple ring-shaped cores. It may be desirable in such embodiments for the length of fiber 10 to be selected so that it matches the self

image lengths or integer multiples thereof for the ring-shaped cores. Using the above equations, the length of fiber 10 can be calculated *a priori* to achieve this goal. An example of such a calculation is as follows. Fig. 8 shows a graph of the first self image length (lower curve) and second self image length (upper curve) as a function of the ring core radius for a double clad fiber having a ring core radius containing active material. With this information, for example, the appropriate length of a fiber having two concentric ring cores containing active material can be determined so that the length of the fiber corresponds to the twice the self image length of the inner core and the self image length of the outer core, resulting in both the inner and outer rings of the fiber being capable of being used as a gain medium. This can be achieved, for example, as 15follows. A radius for the inner ring is selected, and its double self image length is determined based upon the point (point A) on the upper graph in Fig. 8 that has the same radius.. A radius for the outer ring is then determined based upon the point (point B) on the lower graph in Fig. 8 that has the same self image length as point A. Other techniques of selecting appropriate fiber lengths for a given number of ring cores will be apparent to those skilled in the art.

The shapes and sizes of the elements of fiber 10 can also be varied as desired. Examples of certain appropriate fiber designs, shapes and sizes are disclosed, for example, in commonly owned U.S. Patent Application Serial No.______________, filed on March 2, 2001, and entitled, "Fiber For Enhancing Energy Absorption". In addition, while systems using side pumping have been described, other systems can also be used. As an example, systems using end pumping can be used. As another example, systems using both end pumping and side pumping can be used.

Furthermore, while systems having one or two single mode fibers have been described, the invention is not limited in this sense. Additional single mode fibers (e.g., passive single mode fibers) can be used (e.g., three single mode fibers, four single mode fibers, five single mode fibers, six single mode fibers, seven single mode fibers, eight single mode fibers, nine single mode fibers, 10 single mode fibers, 11 single mode fibers, 12 single mode fibers, etc) following the general principles discussed herein.

Other embodiments are in the claims.

WHAT IS CLAIMED IS:

1. A fiber, comprising:
a first region;
a core surrounding the first region, the core comprising an active material; and
a first cladding surrounding the core.

2. The fiber of claim 1, wherein the core is ring-shaped.

3. The fiber of any of the preceding claims, wherein the active material comprises rare earth meal ions.

4. The fiber of any of the preceding claims, wherein the core comprises a multimode core.

5. The fiber of any of the preceding claims, wherein the core comprises a rare earth-doped material.

6. The fiber of any of the preceding claims, wherein the core comprises a silica material and ions of a rare earth metal.

7. The fiber of any of the preceding claims, wherein the first region comprises a silica 20 material.

8. The fiber of any of the preceding claims, wherein the first region has an index of refraction that is less than an index of refraction of the core.

9. The fiber of any of the preceding claims, wherein the first cladding comprises a silica material.

10. The fiber of any of the preceding claims, wherein the first cladding has an index of refraction that is less than an index of refraction of the core.

11. The fiber of any of the preceding claims, further comprising a second cladding surrounding the first cladding.

12. The fiber of claim 11, wherein the second cladding comprises a polymer material.

13. The fiber of claim 11, wherein an index of refraction of the first cladding is greater than an index of refraction of the second cladding.

14. The fiber of any of the preceding claims, wherein the fiber is a multimode fiber.

15. A system, comprising: a first fiber, comprising:
a first region;
a first core surrounding the first region, the core comprising an active material; and
a first cladding surrounding the core; and
a second fiber having a second core, the second fiber being connected to the first fiber so that energy can propagate between the first and second cores.

16. The system of claim 15, wherein the first fiber is a multimode fiber.

17. The system of claim 16 or claim 17, wherein the second fiber is a single mode fiber.

18. The system of any of claims 15-17, further comprising an energy source.

19. The system of any of claims 15-18, further comprising a coupler configured to couple energy emitted by the energy source to the first core.

20. The system of any of claims 15-19, wherein the core of the first fiber is ring-shaped.

21. The system of any of claims 15-20, wherein the active material comprises rare earth meal ions.

22. The system of any of claims 15-21, wherein the core of the first fiber comprises a multimode core.

23. The system, of any of claims 15-22, wherein the core comprises a rare earth-doped material.

24. The system of any of claims 15-23, wherein the first region comprises a silica material.

25. The system of any of claims 15-24, wherein the first region has an index of refraction that is less than an index of refraction of the core of the first fiber.

26. The system of any of claims 15-25, wherein the first cladding comprises a silica material.

27. The system of any of claims 15-26, wherein the first cladding has an index of refraction that is less than an index of refraction of the core of the first fiber.

28. The system of any of claims 15-27, further comprising a second cladding surrounding the first cladding.

29. The system of claim 28, wherein the second cladding comprises a polymer material.

30. The system of claim 28, wherein an index of refraction of the first cladding is greaterthan an index of refraction of the second cladding.

31. The system of any of claims 15-30, wherein the system is arranged in aside pump configuration.

32. The system of any of claims 15-31, wherein the system is arranged in an end pump configuration.

33. The system of any of claims 15-32, further comprising at least one additional fiber.

34. The system of any of claims 32, wherein the at least one additional fiber has a core connected to the first core so that energy can propagate therebetween.

35. The system of any of claims 33-34, wherein the at least one additional fiber is a single mode fiber.

36. The system of any of claims 33-35, wherein the at least one additional fiber is a passive single mode fiber.

37. The system of any of claims 15-36, wherein the second fiber is a passive single mode fiber.

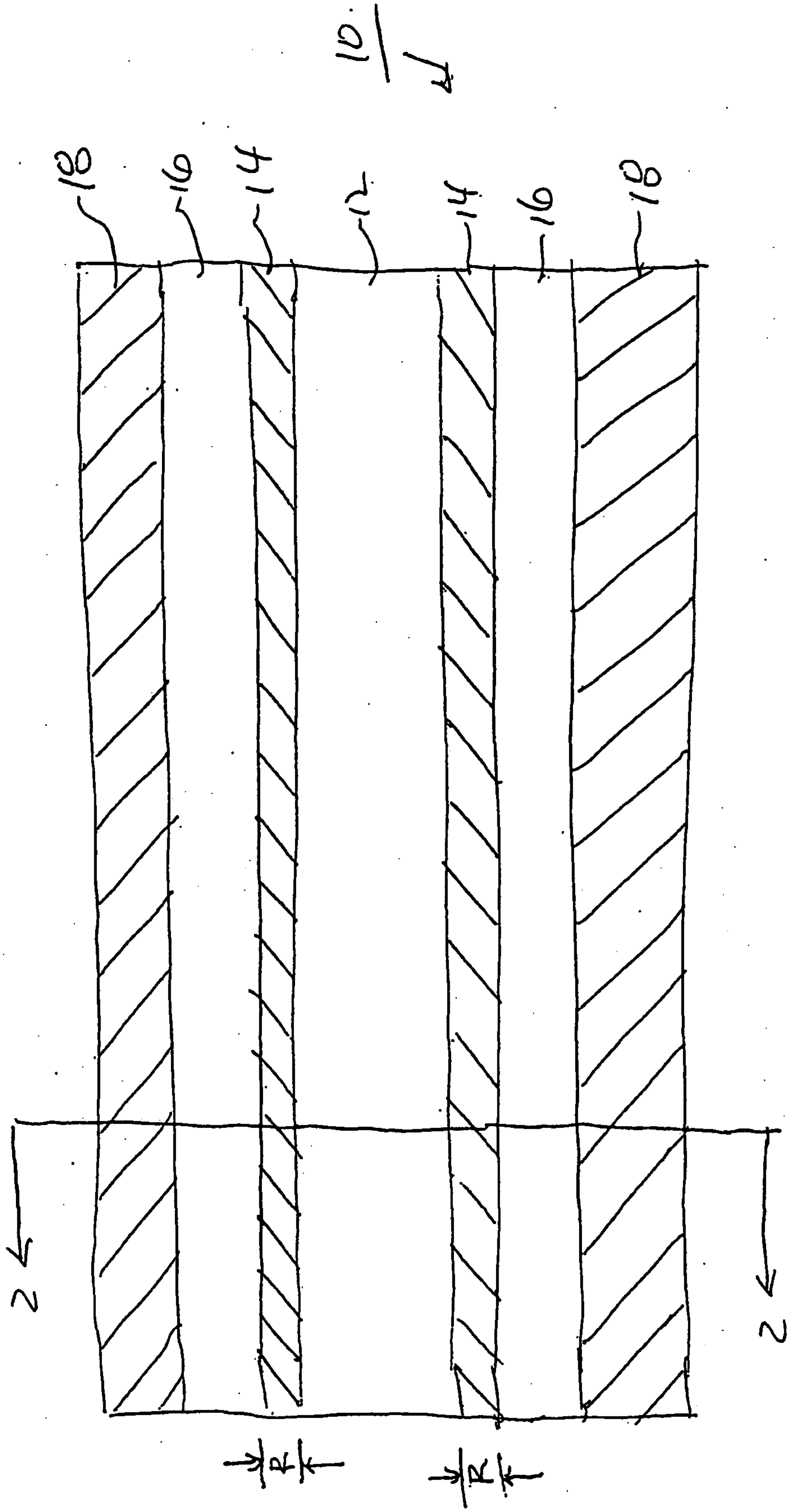


Fig. 1

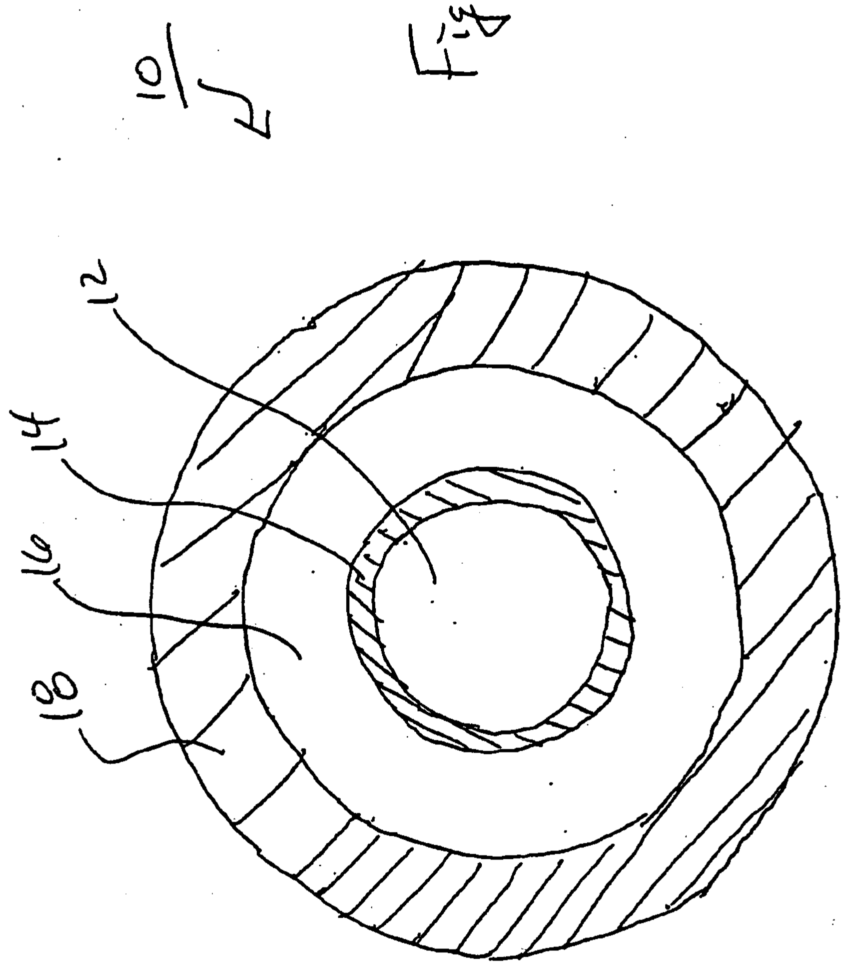


Fig. 2A

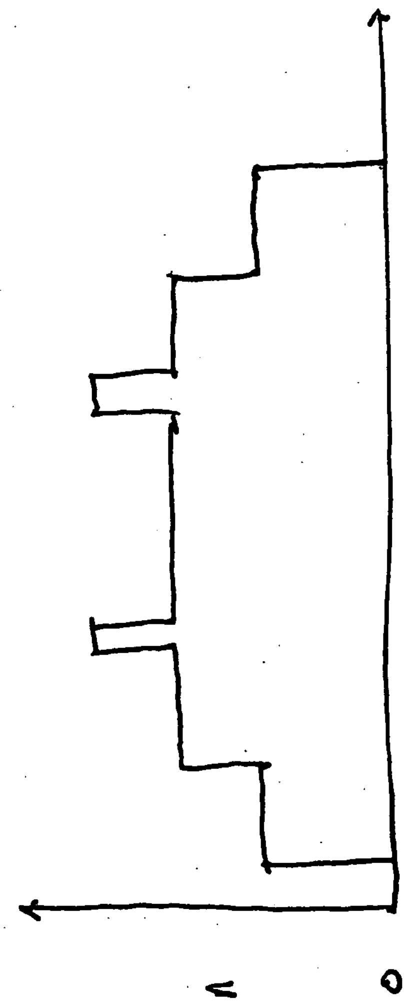


Fig. 2B

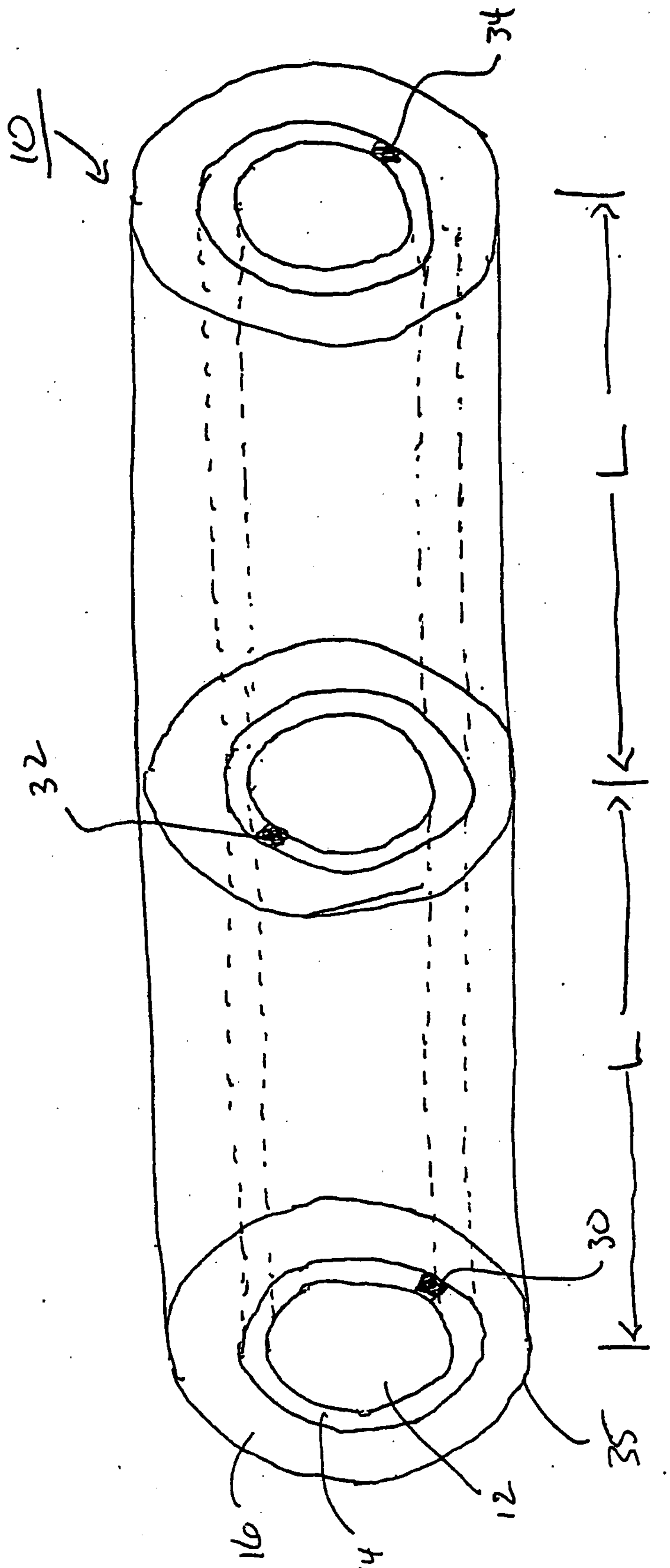


Fig. 3

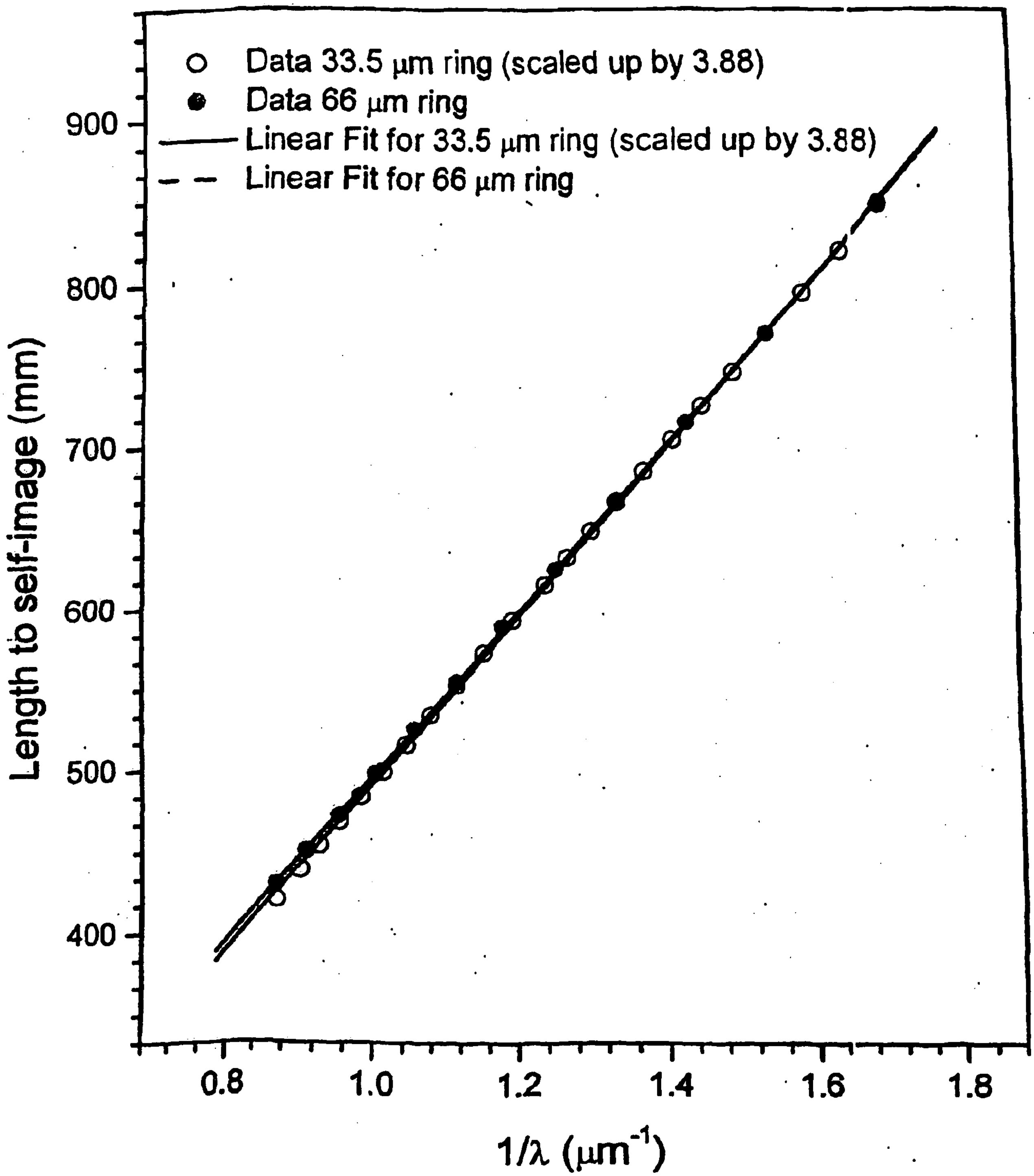

Data 33.5 μm ring (scaled up by 3.88)
Data 66 μm ring
Linear Fit for 33.5 μm ring (scaled up by 3.88)
Linear Fit for 66 μm ring
Length to self-image (mm)
900
800
700
600
500
400
0.8
1.0
1.2
1.4
1.6
1.8
1/λ (μm^{-1})

Fig. 4

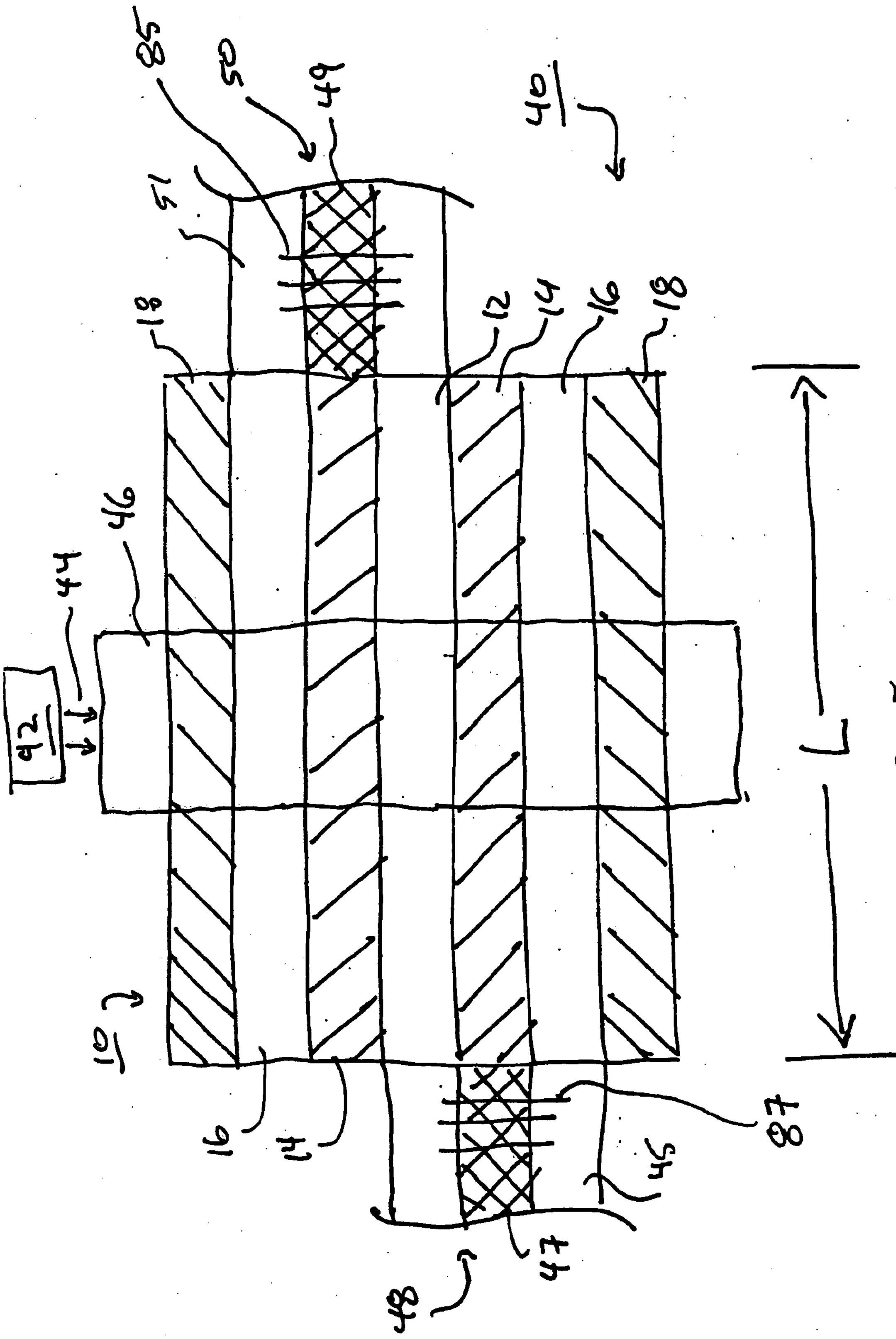


Fig. 5

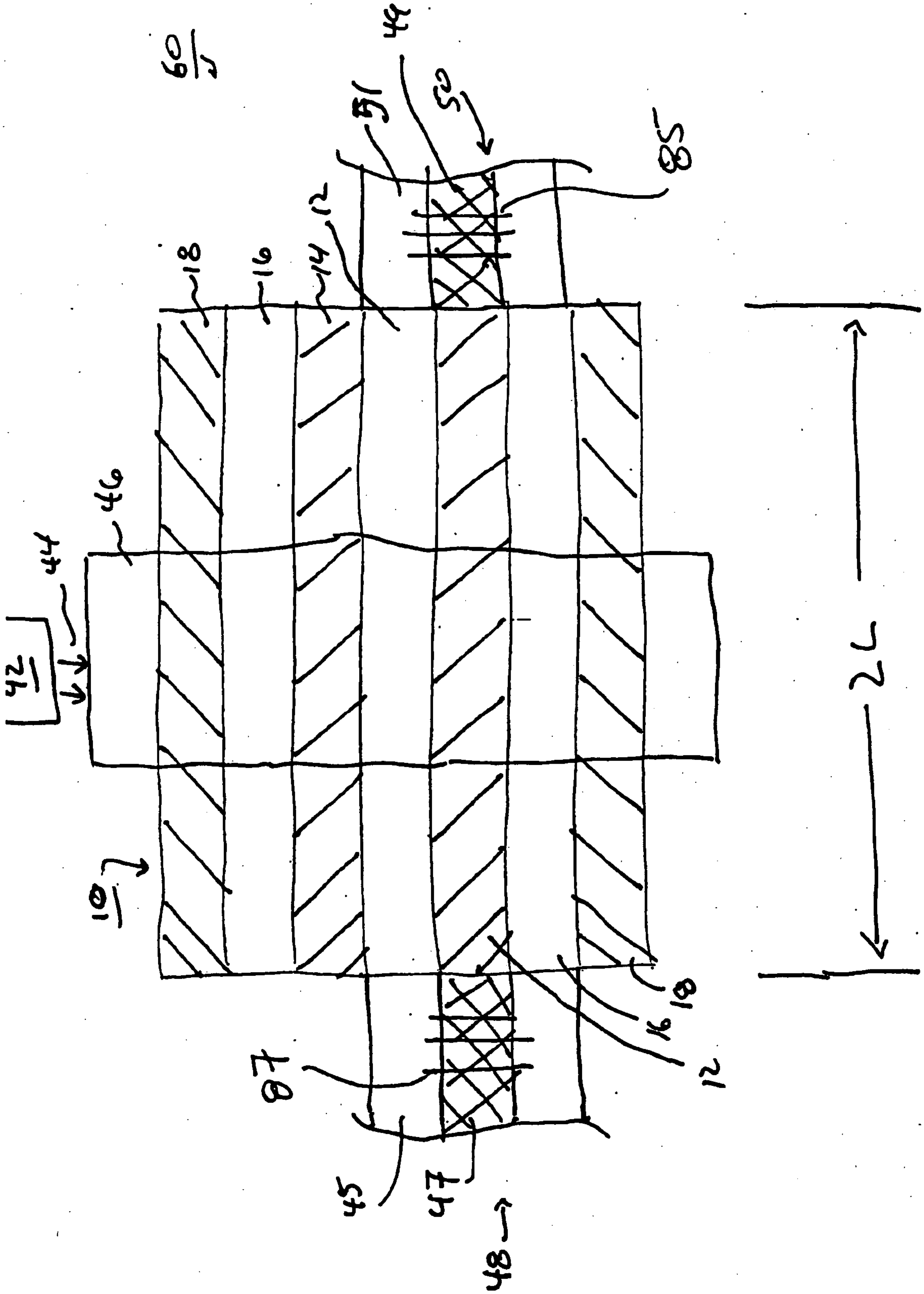


Fig. 6

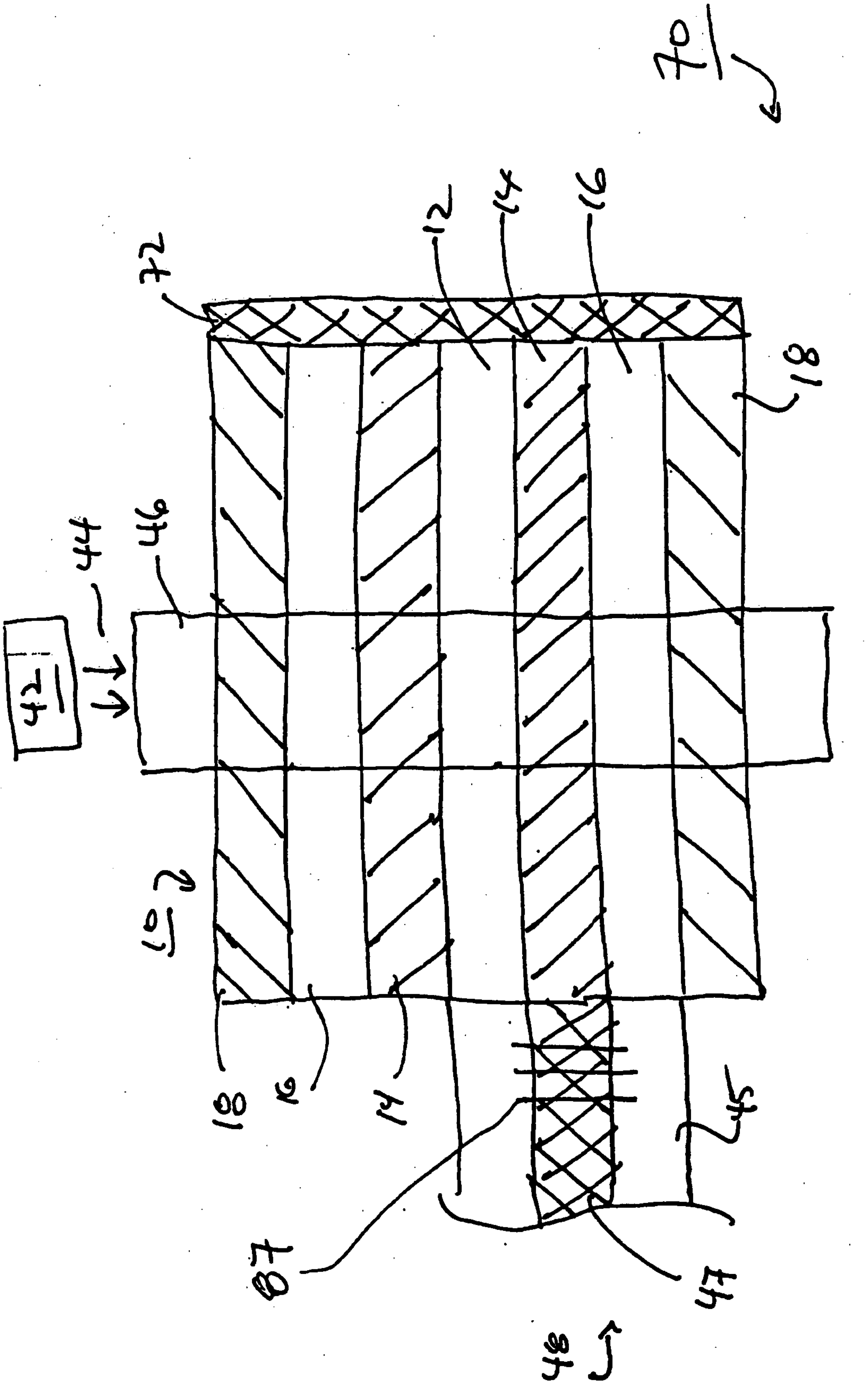


Fig. 7

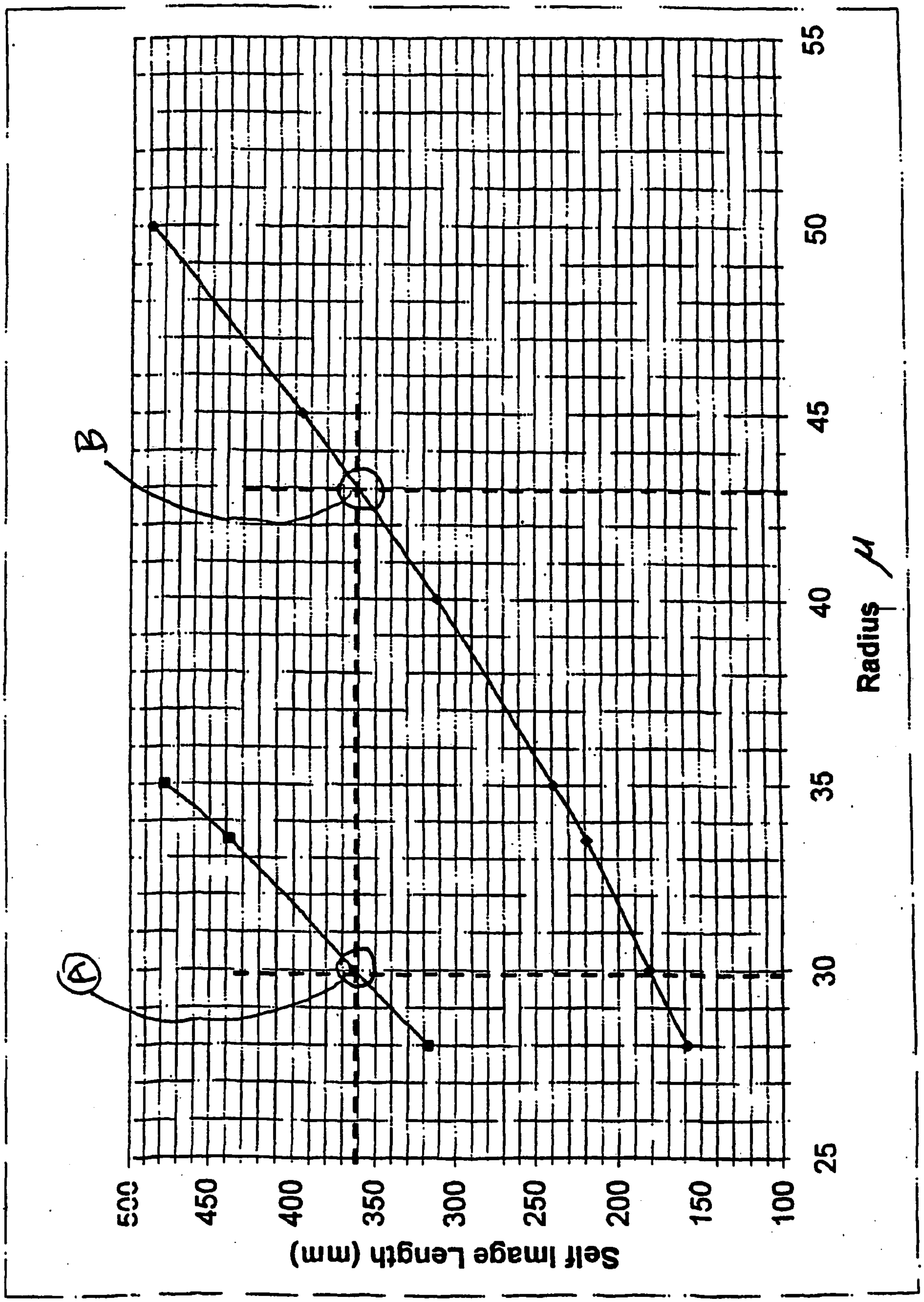

Self Image Length (mm)
500
450
400
350
300
250
200
150
100
Radius μ
25
30
35
40
45
50
55
A
B

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/09513

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 6/32; H01S 3/06
US CL : 385/126, 127l 359/341.1; 372/6
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 385/126, 127l 359/341.1; 372/6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,043,930 A (INAGAKI) 28 March 2000, (28/03/2000) see column 4 lines 10-40.	1-3
X	US 6,192,179 B1 (BERKEY et al) 20 Feburary 2001, (20/02/2001) see column 3 lines 46-58.	1-3, 15, 16
X	US 6,018,533 A (KRIVOSHLYKOV) 25 January 2000, (25/01/2000) see abstract and Fig. 1A.	1-3, 15, 16
X	US 5,530,709 A (WAARTS et al) 25 JUNE 1996, (25/06/1996) see column 5 line 54 - column 6 line 10.	1-3
A	US 6,081,369 A (WAARTS et al) 27 JUNE 2000, (27/06/2000) see column 10 lines 13-36.	1-3, 15, 16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 JULY 2002	08 AUG 2002

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer
JULIANA K. KANG
Telephone No. (703) 305-6259

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/09513

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-14 and 17-37
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.